impacts of chemically toxic materials, and estimates of atmospheric radiological doses to the local population.

The model used to evaluate long-term impacts of radioactive materials in the groundwater simulates the release and transport of radionuclides away from the repository into the unsaturated zone, through the unsaturated zone, and ultimately through the saturated zone to the accessible environment. Analysis of long-term performance depends greatly on the underlying process models necessary to provide thermal-hydrologic conditions, near-field geochemical conditions, unsaturated zone flow fields, and saturated zone flow fields as a function of time. Using these underlying process models involves multiple steps that must be performed sequentially before modeling of the overall system can begin.

Figure I-1 shows the general flow of information between data sources, process models, and the TSPA model. Several process-level computer models are identified in Figure I-1. Examples are the site- and drift-scale thermal hydrology model and the saturated zone flow and transport model. The process models are very large and complex computer software programs used in detailed studies to provide information to the TSPA model. These process models are generally where fundamental laboratory and field data are introduced into the modeling. The subsystem and abstracted models section of the figure encompasses those portions of the TSPA model that are modeled within the GoldSim program. Examples are the unsaturated zone flow fields and the biosphere dose conversion factors. These models are generally much simpler than the process models. They are constructed to represent the results of the more detailed process modeling studies. Often they are simple functions or tables of numbers. This is the process referred to as *abstraction*. It is necessary for some of these subsystem models to be quite complex, even extensive computer codes. The ultimate result sought from modeling long-term performance is a characterization of radiological dose to humans with respect to time, shown at the top of the TSPA section of the figure. This is accomplished by assessing behavior at intermediate points and "handing" off the results to the next subsystem in the primary release path.

ABSTRACTION

Abstraction is the distillation of the essential components of a process model into a suitable form for use in a TSPA. The distillation must retain the basic intrinsic form of the process model but does not usually require its original complexity. Model abstraction is usually necessary to maximize the use of limited computational resources while allowing a sufficient range of sensitivity and uncertainty analyses.

I.2 Total System Performance Assessment Methods and Models

DOE conducted analyses for this EIS to evaluate potential long-term impacts to human health from the release of radioactive materials from the Yucca Mountain Repository. The analyses were conducted in parallel with, but distinct from, the TSPA calculations for the site suitability evaluation. The methodologies and assumptions are detailed in the *Total System Performance Assessment for the Site Recommendation* (DIRS 153246-CRWMS M&O 2000, all), and the *FY01 Supplemental Science and Performance Analyses* (DIRS 155950-CRWMS M&O 2001, all). These two versions of the model are referred to respectively here as the "Site Recommendation model" and the "Supplemental Science and Performance Analyses model." Note that the Supplemental Science and Performance Analyses model starts with the Site Recommendation model and includes incremental enhancements to several parts of the Site Recommendation model. Further changes were made to the model to meet distinct requirements of this EIS. These changes are discussed in more detail in Section I.4 and in DIRS 157307-BSC (2001, Enclosure 1). In summary, the changes are as follows:

- The biosphere dose conversion factors are based on the Reasonably Maximally Exposed Individual (RMEI) defined in 40 CFR 197.21.

- The length of the saturated zone simulated in the performance-assessment model extends from the edge of the repository to where the principal flow path crosses north latitude 36 degrees 40 minutes 13.6661 seconds, as the point where the RMEI would reside. This location is approximately 2 kilometers (1.2 miles) north of the intersection of U.S. Route 95 and Nevada State Route 373, a location formerly known as "Lathrop Wells" and currently known as "Amargosa Valley," that is approximately 20 kilometers (12 miles) downgradient from the repository.

- The groundwater protection standard using an annual water usage of 3.7 million cubic meters per year (exactly 3,000 acre-feet per year) was used in calculating the gross-alpha activity, the total radium concentration, and the total organ dose. All other concentrations were calculated using the same water usage as the Site Recommendation and the Supplemental Science and Performance Analyses models.

- The analysis used the waste inventory that was presented in *Inventory Abstraction* (DIRS 154841-BSC 2001, all). The difference between this inventory and that used in the Site Recommendation and Supplemental Science and Performance Analyses models is that for analysis purposes, U.S. Navy spent nuclear fuel is conservatively modeled as commercial spent nuclear fuel (DIRS 152059-BSC 2001, all and DIRS 153849-DOE 2001, Section 4.2.6.3.9, p. 4-257) and not as DOE-owned spent nuclear fuel.

- Waste package corrosion for the calculations in this report was due to general corrosion independent of temperature.

- The process-level lower-temperature repository operating mode thermal-hydrologic results were corrected to include radiation heat transfer.

- The model was expanded to accommodate inventories other than that for the Proposed Action.

The TSPA is a comprehensive systems analysis in which models of appropriate levels of complexity represent all important features, events, and processes to predict the behavior of the system being analyzed and to compare this behavior to specified performance standards. In the case of the proposed Yucca Mountain Repository system, a TSPA must capture all of the important components of both the engineered and the natural barriers. In addition, the Yucca Mountain TSPA must evaluate the overall uncertainty in the prediction of waste containment and isolation, and the risks caused by the uncertainty in the individual component models and corresponding parameters.

The components of the Yucca Mountain Repository system include five major elements that the TSPA must evaluate for the nominal scenario:

- The natural environment unperturbed by the presence of underground openings or emplaced wastes

- Perturbations to the natural system caused by construction of the underground facilities, waste emplacement, and expected natural events (such as seismic behavior)

- The long-term degradation of the engineered components designed to contain the radioactive wastes

- The release of the radionuclides from the engineered containment system

- The migration of these radionuclides through the engineered and natural barriers to the biosphere and their potential uptake by people, leading to a radiation dose consequence

The analysis included models associated with such disruptive events as volcanism and human intrusion (drilling). Sections I.2.10 and I.2.11 provide an overview of the processes and the models used to represent these disruptive events.

The EIS analysis of long-term performance represents a "snapshot in time," and ongoing work will help refine that snapshot. In the meantime, DOE believes the results of this EIS analysis are conservative estimates, and that work currently in progress or planned will increase confidence in the overall modeling approach.

The calculations for the TSPA model and calculations for this EIS were performed within a probabilistic framework combining the most likely ranges of behavior for the various component models, processes, and related parameters. In some cases, bounding conservative values were used where the available data did not support development of a realistic range. This appendix presents the results as time histories of annual radiological dose to an individual over 10,000 and 1 million years following repository closure. As noted above, the TSPA model implements some of the individual process models directly, while other process models run outside the TSPA model to produce *abstractions* in the form of data tables, response surfaces, or unit-response functions. The TSPA model provides a framework for incorporating these abstractions and integrating them with other subsystem models. This is done in a *Monte Carlo* simulation-based methodology to create multiple random combinations of the likely ranges of the parameter values related to the process models. Probabilistic performance of the entire waste-disposal system was computed in terms of radiological dose to individuals at selected distances from the repository.

MONTE CARLO METHOD: UNCERTAINTY

An analytical method that uses random sampling of parameter values available for input into numerical models as a means of approximating the uncertainty in the process being modeled. A Monte Carlo simulation comprises many individual runs of the complete calculation using different values for the parameters of interest as sampled from a probability distribution. A different outcome for each individual calculation and each individual run of the calculation is called a *realization* (DIRS 153246-CRWMS M&O 2000, p. A-55).

The methodology for analysis of long-term performance for this EIS draws on the extensive analyses performed in support of the TSPA model. Most of the process models (and their abstractions) developed for the TSPA model were used directly in the analyses described in this appendix. Components that were modified to account for the additional analyses considered in this EIS are emphasized in this appendix. However, for continuity, the sections that follow include a general overview of all the elements of the TSPA model.

I.2.1 FEATURES, EVENTS, AND PROCESSES

The first step in the TSPA is to decide which representations of possible future states of the proposed repository (scenario classes and scenarios) are sufficiently important to warrant quantitative analysis. The TSPA model can analyze only a relatively small number of the essentially infinite combinations of features, events, and processes that could affect the system. It is important, therefore, that the scenarios chosen for analysis provide a sound basis for evaluating the performance of the repository. Specifically, the chosen scenarios must be representative of the conditions of greatest relevance to forecasting the long-term behavior of the system.

The first step in developing scenarios is to make an exhaustive list of features, events, and processes that could apply to the repository system. The initial list is developed using a number of resources:

- Lists previously compiled by other organizations on an international scale (such as the Nuclear Energy Agency of the Organization for Economic Cooperation and Development)
- Lists compiled during earlier stages of site exploration
- Lists developed by experts from the Yucca Mountain Project and outside consultants

FEATURES, EVENTS, AND PROCESSES

Features are physical parts of the system important to how the system could perform. Examples include the Ghost Dance Fault and the Topopah Spring stratigraphic unit.

Events are occurrences in time that can affect the performance or behavior of the system. Events tend to happen in short periods in comparison to the period of concern, and they tend to occur at unpredictable times. Examples include a volcanic intrusion or a human intrusion by drilling.

Processes are physical and chemical changes that occur over long periods, tend to be 100-percent likely to occur, and are predictable. Examples include corrosion of the metals in the waste package and dissolution of waste form materials after exposure to water.

The starting list is subjected to a comprehensive screening process. Features, events, and processes are screened from the list based on several criteria:

- Obvious inapplicability to the specific site (for example, the starting list included processes that occur only in salt, a rock type known to be not present at Yucca Mountain).
- Very low probability of occurrence (for example, meteorite impact)
- Very low consequence to the closed repository (for example, an airplane crash)
- Exclusion by regulatory direction (for example, deliberate human intrusion)

The remaining features, events, and processes are combined in scenarios that incorporate sequences of events and processes in the presence of features. The three main scenarios evaluated are:

- Nominal scenario (generally undisturbed performance with only seismic events)
- Volcanism scenario (eruption through the repository or intrusion of igneous material into the repository)
- Inadvertent human intrusion scenario.

When the scenarios described above were formed from the Features, Events, and Processes retained after screening, the focus was on the 10,000-year compliance period. Therefore in the screening documentation the reliance on a limit of 10,000-years was sometimes expressed. This EIS is charged by 40 CFR Part 197 with the task of reporting the peak dose values whenever they occur during the period of geologic stability. As can be seen by the results in this EIS, the peaks occur at times considerably longer than 10,000 years and it was necessary to carry out the analysis for 1 million years in order to establish the peak dose. Because the TSPA model used to generate all the results in the EIS is the same model that resulted from the Features, Events, and Processes screening it is important to explore the possible effect of the use of a 10,000 limit when screening Features, Events, and Processes. The following discussions are provided by the Features, Events, and Processes screening staff for that purpose (DIRS 155937-Freeze 2001, all). In addition to the discussions from the DIRS 155937-Freeze (2001, all) document there is also a short discussion of seismic Features, Events, and Processes. For a comprehensive discussion of all the Features, Events, and Processes the reader is referred to the Features, Events, and Processes database documentation (DIRS 154365-Freeze, Brodsky, and Swift 2001, all).

Note that in numbers given in the headings or text of Sections I.2.1.1 through I.2.1.7 (in the form "FEP No. X.X.X.X.X") refer to an index number from the Features, Events, and Processes database (DIRS 154365-Freeze, Brodsky, and Swift 2001, all).

I.2.1.1 Tectonic Activity (FEP No. 1.2.01.01.00)

The current strain rate is indicated by DIRS 118952-Savage, Svarc, and Prescott (1999, p. 17627) as less than 2 millimeters per year (0.08 inch per year) and is reflected in local slip rates of between 0.001 and 0.03 millimeters per year (0.0004 and 0.001 inches per year). At the highest rate, the total slip after 10,000 years would be on the order of 0.010 to 0.3 meters (0.03 to 1 foot), but after 1 million years could be on the order of 1 to 30 meters (3.3 to 98 feet). The increased rates of tectonic and igneous activity in the geologic past (and leading to the 30-meter value) were associated with greater crustal strain rates than exist currently. In particular, DIRS 118942-Fridrich (1999, all) indicate extension of the Crater Flat structural basin to have been on the order of 18 to 40 percent between about 12.6 and 11.6 million years ago during the major pulse of extension, with the rate of extension declining exponentially since 11.6 million years ago. From the late Quaternary through the present, the rate of extension is less than 1 percent of the initial rate. These studies suggest that crustal extension rates are likely to vary insignificantly or to decrease with time. As a consequence, assumption of the existing tectonic setting and strain rates for periods out to 1 million years, for purposes of the EIS, is reasonable, although quantification of associated displacements would exhibit a time-dependent increase in uncertainty.

The median probability for exceeding fault displacements greater than 3 meters (10 feet) on the Solitario Canyon Fault is approximately 0.0001 in 10,000 years, and the median and mean probability for fault displacement on intrablock faults of 2 meters (6.6 feet) or greater is less than 0.0001 in 10,000 years (DIRS 100354-USGS 1998, all). The projected values assume that the tectonic strain rate is either equal to or less than the existing strain rate. Projection and use of these displacements for a 1-million-year time frame is appropriate, but is accompanied with an increase in uncertainty in the probable displacement value.

Based on the repository design, the drifts could accommodate as much as 2 meters (6.6 feet) of vertical displacement on intrablock faults before waste package shearing conditions could occur and, with the use of set-backs, at least 3 meters (10 feet) of offset could be accommodated in the Solitario Canyon Fault, and possibly more if distributed faulting is considered. Hypothetical models at the mountain-scale also suggest that flow in fault zones and fractures would not be significantly affected by displacement of as much as 10 meters (33 feet). The tolerance values are not time-dependent. The projected total slip values at 1 million years (1 to 30 meters, or 3.3 to 98 feet) are of the same order of magnitude as the tolerance limit (1 to 10 meters, or 3.3 to 33 feet).

Because the tolerance values are the same order of magnitude as the projected total slip, and because the tectonic setting and history of the site suggest that strain rates will either vary insignificantly or decrease, the assumptions and models in the TSPA related to tectonic activity should be reasonable and applicable for the 1-million-year time span as well.

I.2.1.2 Erosion/Denudation (FEP No. 1.2.07.01.00)

Erosion is a process that is expected to be ongoing at Yucca Mountain. The maximum erosion over 10,000 years is expected to be less than 10 centimeters (3.9 inches) (DIRS 100520-YMP 1993, p. 55), which is within the range of existing surface irregularities.

After 1 million years the maximum total erosion would be 10 meters (33 feet), assuming the erosion rate estimated for the next 10,000 years remained constant for the next 1 million years. This maximum value is far less than the amount required to expose waste at the land surface, and possible effects would therefore be limited to changes in infiltration and flow in the unsaturated zone. Local changes of as much as 10 meters would represent a small change relative to the hundreds of meters (thousands of feet) of topographic variability already incorporated in the infiltration model used to calculate flow in the unsaturated zone. The effects of erosion on infiltration are therefore considered negligible. Erosion due to normal surface processes at Yucca Mountain is therefore excluded from the 1 million-year analyses.

Future climate projections extending to 10,000 years (DIRS 136368-USGS 2000, all; DIRS 153038-CRWMS 2000, all) indicate that, although the climate is expected to evolve to a cooler, wetter climate, conditions will be that of a glacial transition or glacial-type climate. As a result, direct glacial erosion and transport is not considered a credible event. Therefore, glacial erosion is excluded on the basis of low probability.

The effects of erosion processes on how radionuclides might accumulate in soils and subsequently enter the biosphere are included (DIRS 136281-CRWMS M&O 2000, Section 6.1.1) for the post-10,000-year period. The effects of erosional processes in the biosphere are considered in an Analysis Model Report titled *Evaluate Soil/Radionuclide Removal by Erosion and Leaching* (DIRS 136281-CRWMS M&O 2000, all) and are considered in *Total System Performance Assessment for the Site Recommendation* (DIRS 153246-CRWMS M&O 2000, Sections 3.9 and 3.10) as part of the peak dose calculations.

I.2.1.3 Periglacial Effects (FEP No. 1.3.04.00.00)

This process refers to climate conditions that could produce a cold, but glacier-free, environment. Results of such a climate could include permafrost (permanently frozen ground). Some consequences of such a condition identified in the secondary Features, Events, and Processes are enhanced erosion due to the freeze/thaw cycle and the trapping of gases in or near the proposed repository.

Global climate change was addressed in the TSPA using a climate model based on paleoclimate information. That is, the record of climate changes in the past was used to predict changes in climate for the future. Because the geologic record indicates that climatic conditions during the Quaternary period (the past 1.6 million years) at no time resulted in plant communities at Yucca Mountain that are consistent with periglacial conditions (DIRS 136281-CRWMS M&O 2000, Section 4.2.4), this process has been excluded on the basis of low probability.

Future climates are described in terms of discrete climate states that are used to approximate continuous variations in climate. The effects of seasonality are included in the climate model by using climate analogs with specific seasonal meteorological records. More specific information about the methods used to predict future climate change and the findings for the climate model is provided in DIRS 136368-USGS (2000, Section 6). Climate modeling is incorporated in the TSPA through the unsaturated zone flow fields, which have different surface-water infiltration as a result of different climates. A description of the modeling methods used for infiltration and how infiltration is affected by climate is in DIRS 136368-USGS (2000, Section 6).

Potential future climate conditions at Yucca Mountain were analyzed in two Analysis Model Reports: *Future Climate Analyses* (DIRS 136368-USGS 2000, all) and *Documentation of Million-Year TSPA* (DIRS 153038-CRWMS 2000, all). The climate at Yucca Mountain for the next 10,000 years is treated as a sequence of three climate states: modern (interglacial) climate for 400 to 600 years, monsoon climate for 900 to 1,400 years, and glacial-transition (intermediate) climate for the balance of the 10,000-year period. The glacial-transition (intermediate) climate occurs either preceding or following the colder, wetter full glacial climate states. Three additional full-glacial climate states are specified during the longer period of 1 million years, with different climate stages synchronized with the earth orbital clock. Full-glacial stages would encompass about 21 percent of the time over the next 1 million years. The intermediate climate would be the dominant climate for the next 1 million years.

I.2.1.4 Glacial and Ice Sheet Effects (FEP No. 1.3.05.00.00)

This process refers to the local effects of glaciers and ice sheets. Paleoclimate records indicate that glaciers and ice sheets have not occurred at Yucca Mountain at any time in the past (DIRS 136368-USGS 2000, Section 6.2). The closest alpine glaciers to Yucca Mountain during the Pleistocene were in the Sierra Nevada of California and possibly the Spring Mountains in Nevada (DIRS 151945-CRWMS M&O 2000, Section 4.2.3.3.6), too far from Yucca Mountain to have any effect on site geomorphology or hydrology. Given the relatively low elevation of Yucca Mountain, there is no credible mechanism by which a glacier could form at the site over the next 10,000 years, and there is no evidence to suggest formation at Yucca Mountain in the next 1 million years. Therefore, this process is excluded on the basis of low probability. Note, however, that the regional climatic effects of ice sheets that might form farther north are included based on a change in climate states.

I.2.1.5 Hydrostatic Pressure on Container (FEP No. 2.1.07.04.00)

A repository at Yucca Mountain would emplace waste above the water table in a fractured, porous medium. Thus, the pressure on the waste package is approximately atmospheric under present conditions. Possible changes in the elevation of the water table due to climate change and tectonic processes have been evaluated (DIRS 153931-CRWMS M&O 2001, Sections 6.2.11 and 6.2.8; DIRS 154826-BSC 2001, Section 6.7.6), and water table fluctuations due to climate change are included in the TSPA model. Even under the wettest future climate states, however, the highest elevation of the water table would be far below the emplacement drifts, and hydrostatic pressure effects on the packages are therefore excluded on the basis of low probability for both 10,000-year and 1-million-year analyses.

I.2.1.6 Soil and Sediment Transport (FEP No. 2.3.02.03.00)

Transport of soil and sediments in the biosphere is discussed in the Analysis Model Reports titled *Evaluate Soil/Radionuclide Removal by Erosion and Leaching* (DIRS 136281-CRWMS M&O 2000, all) and *Nominal Performance Biosphere Dose Conversion Factor Analysis* (DIRS 152539-CRWMS M&O 2001, all). The results of these analyses are used in Sections 3.9 and 3.10 of the TSPA–Site Recommendation (DIRS 153246-CRWMS M&O 2000). Aeolian and fluvial transport of contaminated volcanic ash has been indirectly included in the TSPA–Site Recommendation igneous disruption scenario through the use of a wind direction fixed toward the critical group for all hypothetical eruptions. As described in Section 3.10 of TSPA–Site Recommendation (DIRS 153246-CRWMS M&O 2000), use of a fixed wind direction compensates for the lack of an explicit model for sediment transport following ash deposition by ensuring that all eruptions would result in the deposition of contaminated ash at the location of the critical group, regardless of the wind direction at the time of the event. The TSPA–Site Recommendation calculations include the probability of eruptive events extending past the 10,000-year regulatory period to calculate peak dose.

Paleoclimate records indicate that glaciers and ice sheets have not occurred at Yucca Mountain at any time in the past (DIRS 136368-USGS 2000, Section 6.2). The closest alpine glaciers to Yucca Mountain during the Pleistocene were in the Sierra Nevada of California and possibly the Spring Mountains in Nevada (DIRS 151945-CRWMS M&O 2000, Section 4.2.3.3.6), too far from Yucca Mountain to have any effect on site geomorphology or hydrology. Given the relatively low elevation of Yucca Mountain, there is no credible mechanism by which a glacier could form at the site within the time frames considered. Therefore, glacial transport of soil and sediments is not considered credible and this process is excluded on the basis of low probability.

I.2.1.7 Seismic Damage to Waste Packages

This discussion refers to the following Features, Events, and Processes:

- Seismic vibration causes container failure (FEP No. 1.2.03.02.00)
- Mechanical impact on waste container and drip shield (FEP No. 2.1.03.07.00)
- Effects and degradation of drip shield (FEP No. 2.1.06.06.00)
- Rockfall – large block (FEP No. 2.1.07.01.00)
- Mechanical degradation or collapse of drift (FEP No. 2.1.07.02.00)

These events all have to do with possible damage to the waste packages or drip shields either directly or indirectly (for example, rock fall) due to seismic events. In the Features, Events, and Processes screening these events were screened out for low consequence because up to 10,000 years the waste packages remain essentially intact (see detailed results in Section I.5) and possess their original design strength. Because the packages are designed to withstand seismic events that are of sufficient likelihood during the 10,000-year period, it follows that a low-consequence screening for the 10,000-year period is justified.

The analysis for the million-year period extended the screening of seismic damage to waste packages throughout that time. This was an analytical assumption based on using the best data and models available for the Final EIS. No quantitative analysis was performed to determine when a waste package might degrade to the point where it could be damaged by a seismic event. However, it is reasonable to expect that peak dose estimates would likely have been higher (by an unknown amount) if the analysis accounted for potential seismic damage of degraded waste packages hundreds of thousands of years into the future.

I.2.2 UNSATURATED ZONE FLOW

Changes in climate over time provide a range of conditions that determine how much water could fall onto and infiltrate the ground surface. Based on current scientific understanding, the current climate is estimated to be the driest that the Yucca Mountain vicinity will ever experience. All future climates were assumed similar to current conditions or wetter than current conditions. The *climate* model provides a forecast of future climates based on information about past patterns of climates (DIRS 153246-CRWMS M&O 2000, p. 3-38 to 3-42). This is generally accepted as a valid approach because climate is known to be cyclical and largely dependent on repeating patterns of earth orbit and spin. The model represents future climate shifts as a series of instant changes. During the first 10,000 years, there are three changes, in order of increasing wetness, from present-day to a monsoon and then to a glacial-transition climate. Between 10,000 years and 1 million years there are 45 changes between six climate states incorporated in the TSPA model (DIRS 153246-CRWMS M&O 2000, p. 3-38):

- Interglacial Climate (same as present day)
- Intermediate Climate (same as the Glacial-transition)
- Intermediate/Monsoon Climate
- Three stages of Glacial Climate of varying infiltration rates

CLIMATE CHANGE

The analysis of long-term performance considered six climate states. Many changes in climate states occur in the simulation over a 1-million-year period after closure. The times of change are keyed to known past cycles for the previous million years as determined by paleoclimatology studies. (DIRS 153246-CRWMS M&O 2000, Figure 3.2-16, p. F3-24).

Precipitation that is not returned to the atmosphere by evaporation or transpiration enters the unsaturated zone flow system. Water infiltration is affected by a number of factors related to climate, such as an increase or decrease in vegetation on the ground surface, total precipitation, air temperature, and runoff. The *infiltration* model uses data collected from studies of surface infiltration in the Yucca Mountain region (DIRS 155950-BSC 2001, Section 3.2.2). It treats infiltration as variable in the region, with more occurring along the crest of Yucca Mountain than along its base. The results of the climate model affect assumed infiltration rates. For each climate, there is a set of three infiltration rates (high, medium, low) and associated probabilities. This forms a discrete distribution that is sampled in the probabilistic modeling. The sampled ranges are described in Tables I-1 and I-2. Whenever a particular climate state is in effect, the associated infiltration rate distribution is sampled for each realization of the simulation.

Table I-1. Average net infiltration rates (millimeters per year) over the unsaturated zone flow and transport model domain for the present-day, monsoon, and glacial transition climate states.[a,b]

Climate	Lower bound	Mean	Upper bound
Present day	1.3	4.6	11.1
Monsoon	4.6	12.2	19.8
Glacial transition	2.5	17.8	33.0

a. Adapted from DIRS 155950-BSC (2001, Table 3.3.2-1).
b. To convert from millimeter per year to inch per year, multiply by 0.03937.

Table I-2. Average net infiltration rates (millimeters per year) over the unsaturated zone flow and transport model domain for full-glacial climate states.[a,b]

Climate	Lower bound	Mean	Upper bound
Glacial, Stage 8/10	33.0[c] (36.0[d])	87.9	151.0
Glacial, Stage 6/16	24.4	87.9	151.0
Glacial, Stage 4	12.9	24.4	87.9

a. Adapted from DIRS 155950-BSC (2001, Table 3.3.2-3).
b. To convert from millimeter per year to inch per year, multiply by 0.03937.
c. Derived using upper-bound intermediate climate meteorological station data (DIRS 155950-BSC 2001, Tables 3.3.1-5, 3.3.1-6).
d. Derived using alternate Stage 6/16 meteorological station data (DIRS 155950-BSC 2001, Tables 3.3.1-5, 3.3.1-6).

Water generally moves downward in the rock matrix and in rock fractures. The rock mass at Yucca Mountain is composed of volcanic rock that is fractured to varying degrees because of contraction during cooling of the original, nearly molten rock and because of extensive faulting in the area. Water flowing in the fractures moves much more rapidly than water moving through the matrix. At some locations, water might collect in locally saturated zones (*perched water*) or might be laterally diverted because of differing rock properties at rock layer interfaces. The overall unsaturated flow system is heterogeneous, and the locations of flow paths, velocities, and volumes of groundwater flowing along these paths are likely to change many times over the life of the repository system. The *mountain-scale unsaturated zone flow* model assumes constant flow over a specific period (taken from the infiltration model) and generates three-dimensional flow fields for three different infiltration boundary conditions, the six different climates described above, and several values of rock properties (DIRS 153246-CRWMS M&O 2000, pp. 3-29 and 3-41). The model is an isothermal model; thermal effects can be neglected because flow would be strongly perturbed only by heat near the emplacement drifts and at early times (DIRS 153246-CRWMS M&O 2000, p. 3-31). The influence of heat near the drifts is dealt with in the thermal hydrology models discussed below. The flow fields from the mountain-scale unsaturated zone flow model are the abstractions that are utilized by the TSPA model while the system model is running. The TSPA model simply switches to the correct flow field for the sampled infiltration rate, as dictated by the current climate state and sampling of the infiltration rate range.

After water returns to the repository walls, it would drip into the repository. The number of seeps that would occur and the amount of water that would be available to drip would be restricted by the low rate at which water flows through Yucca Mountain, which is in a semiarid area. Drips would occur only if the hydrologic properties of the rock mass caused the water to concentrate enough to feed a seep. Over time, the number and locations of seeps would increase or decrease, corresponding to increased or decreased infiltration based on changing climate conditions. The *seepage flow* model calculates the amount of seepage that could occur based on input from the unsaturated zone flow model (DIRS 155950-BSC 2001, Section 4.3). The basic conceptual model for seepage suggests that openings in unsaturated rock act as capillary barriers and divert water around them. For seepage to occur in the conceptual model, the rock pores at the drift wall would have to be locally saturated. Drift walls could become locally saturated by either disturbance to the flow field caused by the drift opening or variability in the permeability field that created channeled flow and local ponding. Of the two reasons, the variability effect is more important. Drift-scale flow calculations made with uniform hydrologic properties suggest that seepage would not occur at expected percolation fluxes. However, calculations that include permeability variations do estimate seepage, with the amount depending on the hydrologic properties and the incoming percolation flux. The seepage abstraction is based on extensive modeling calibrated by measurements from onsite testing in the Exploratory Studies Facility (DIRS 153246-CRWMS M&O 2000, pp. 3-35 to 3-36, and DIRS 155950-BSC 2001, Section 4.3.1.5). The seepage abstraction includes probability distributions for the fraction of waste packages encountering seepage and the seep flow rate, accounting for parameter uncertainty, spatial variability, and other effects, such as focusing (DIRS 155950-BSC 2001, Section 4.3.2), episodicity (DIRS 155950-BSC 2001, Section 4.3.5), rock bolts (DIRS 155950-BSC 2001, Section 4.3.3), drift degradation (DIRS 155950-BSC 2001, Section 4.3.4) and coupled processes (DIRS 155950-BSC 2001, Sections 4.3.5 through 4.3.7). All of these parameters are input as uncertainty distributions that are sampled in the probabilistic modeling.

I.2.3 ENGINEERED BARRIER SYSTEM ENVIRONMENTS

Engineered barrier system environments refer to the thermodynamic and chemical environments in the emplacement drifts. These environments control processes that affect the components of the engineered barrier system (such as the drip shields, waste packages, and waste forms). The environmental characteristics of importance are the degradation of the drift (including rock fall into the drift), temperature, relative humidity, liquid saturation, pH, liquid composition, and gas composition. Thermal effects on flow and chemistry outside the drifts are also important because they affect the amount and composition of water and gas entering the drifts. The engineered barrier system environments are important to long-term repository performance because they would help determine degradation rates of components, quantities and species of mobilized radionuclides, transport of radionuclides through the drift into the unsaturated zone, and movement of fluids into the unsaturated zone.

The *drift degradation model* describes the deterioration of the rock mass surrounding the repository emplacement drifts. Deterioration would occur by failure of fractures that bound blocks of rock at the drift walls and the resultant falling of those blocks into the drift. The deterioration is described in terms of key block analysis (DIRS 153246-CRWMS M&O 2000, pp. 3-43), which is a tool used for the following purposes:

- Provide a statistical description of block sizes formed by fractures around the emplacement drifts
- Estimate changes in drift profiles due to fallen blocks of rock
- Provide an estimate of the time required for significant drift deterioration to occur.

Key blocks would be formed by the intersection of three or more fracture planes with the excavation. Key blocks could become dislodged and fall because of seismic effects. A detailed analysis, based on observation and testing, was used to develop an abstraction of block failures and rockfalls. The abstraction is in the form of tables of numbers and volumes of blocks falling per unit length of emplacement drift as a function of time due to seismic and other effects.

Within the TSPA model, most engineered system calculations were performed for a limited number of waste package locations. In the model, each of these locations is representative of a group of waste packages with similar environmental characteristics. Radionuclide releases, for example, were calculated for a representative waste package and then scaled up by the number of failed waste packages in the group. Not all waste packages in a group would fail at the same time because additional variability is included in the waste package degradation calculation. The waste package groups (referred to as *bins*) are not based on physical location. Rather, the bins are based on infiltration patterns (that is, divided into categories of specific ranges of infiltration rate) and on waste type (that is, codisposal packages and commercial spent nuclear fuel packages) (DIRS 153246-CRWMS M&O 2000, Section 3.3.2).

The heat generated by the decay of nuclear materials in the repository would cause the temperature of the surrounding rock and waste packages to rise from the time of emplacement until a few hundred years after repository closure (DIRS 153246-CRWMS M&O 2000, Figure 3.3-9, p. F3-33). The water and gas in the heated rock would be driven away from the repository during this period, referred to in this EIS as the *thermal pulse*. The thermal output of the materials would decrease with time; eventually, the rock would return to its original temperature, and the water and gas would flow back toward the repository. The *multi-scale thermal hydrology model* is used to study the processes that would govern the temperature, relative humidity, liquid saturation, liquid flow rate, liquid evaporation rate, and thermal effects on seepage. Drift-scale modeling includes coupling of drift-scale processes with mountain-scale processes to account for effects such as faster cooling of waste packages near the edge of the repository, as compared to waste packages near the center. A multi-scale modeling and abstraction method was developed to couple drift-scale processes with mountain-scale processes (DIRS 153246-CRWMS M&O 2000, pp. 3-56 to 3-58, and DIRS 155950-BSC 2001, Section 5.3.1). In addition, a coupled *thermal-hydrology-chemistry model* was developed to study the coupled effects on the heat, flow and chemistry of the system (DIRS 153246-CRWMS M&O 2000, p. F3-33). The results of these detailed modeling studies are abstracted as response surfaces of temperature, humidity, and liquid saturation.

The source term for transport of radionuclides from the proposed repository in the unsaturated zone and saturated zone water flow is the radionuclide flux from inside the drifts to the unsaturated zone rock. That flux would be influenced by the in-drift engineered barrier system chemical environment. The *engineered barrier system geochemical environment models* (DIRS 153246-CRWMS M&O 2000, pp. 3-62 to 3-69 and DIRS 155950-BSC 2001, Sections 6.3.1 and 6.3.3) were used to study the changing composition of gas, water, colloids, and solids in the emplacement drifts under the perturbed conditions of the repository. Several submodels were integrated to provide detailed results and interpretations. The major composition changes would be caused by the thermal loading of the system and the emplacement of large masses of materials that can react with water and gas in the system. The system would continually change due to the heating and cooling cycle. Because the emplaced materials would be very different from the host rock, the entering water and gas would be altered by reaction with these materials. Emplaced materials could be an additional source of colloids that could affect how radionuclides were transported in the aqueous system. The engineered barrier system geochemical environment models produce detailed results that are then abstracted for the following processes:

- Water and cement interactions
- Gas and water interactions
- Evaporation of water and condensation of vapor
- Salts precipitation and dissolution
- Microbial activity and effects
- Corrosion and degradation of engineered barrier system components

- Water and invert interactions
- Water and colloids interactions.

The abstractions were integrated into the TSPA model as chemistry lookup tables for various periods, parametric results, and sometimes enhancement or correction factors for other processes such as corrosion or transport (DIRS 153246-CRWMS M&O 2000, pp. 3-69 to 3-79 and DIRS 155950-BSC 2001, Sections 5.3.2.2 and 6.3.1.6).

The location of the seeps would depend to some extent on the natural conditions of the rock but also on the alterations caused by the construction of a repository. Alterations, such as increased fracturing, would be caused by mechanical processes related to drilling the drifts or by thermal heating and expansion of the drift walls. The alterations in the seepage could also be caused by chemical alterations occurring as the engineered materials dissolved in water and reprecipitated in the surrounding rock, closing the pores and fractures. The chemistry in the drift would change continually because of the complex interactions between the incoming water, circulating gas, and materials in the drift (for example, concrete from the liner or metals in the waste package). The changes in chemistry would be strongly influenced by heat during the thermal pulse.

The seepage would flow through the engineered barrier system along eight pathways. These pathways are (DIRS 155950-BSC 2001, Sections 8.2 and 8.3):

1. Seepage flux entering the drift—This would be the liquid flow into the engineered barrier system.

2. Flow through the drip shield—Liquid flux through the drip shield would begin after holes formed due to general corrosion.

3. Diversion around the drip shield—The portion of the flux that did not flow through the drip shield was assumed to bypass the invert and flow directly into the unsaturated zone.

4. Flow through the waste package—The fluid flow through the waste package would be based on the presence of holes due to general corrosion. The liquid flux through any holes in the waste package is calculated using a flux splitting algorithm that incorporates the fraction of the waste package or drip shield that has openings. This algorithm considers the projected patch area on a breached waste package or drip shield.

5. Flow diversion around the waste package—The portion of the flux that did not flow through the drip shield and onto the waste package was assumed to bypass the waste form and flow directly onto the invert.

6. Evaporation from the invert condensation underneath the drip shield—The magnitude of the evaporative flux from the invert would be based on the thermal-hydrologic abstraction.

7. Flow from the waste package to the invert—All flux from the waste package would flow to the invert, independent of breach location on the waste package. The presence of the emplacement pallet was ignored, and the waste package was assumed to be lying on the invert so a continuous liquid pathway for diffusive transport would exist at all times.

8. Flow through the invert into the unsaturated zone—Flow could be by advection or diffusion. The model accounts for sorption in the invert.

The model accounts for the evaporation of some of the liquid flux to the drip shield (DIRS 155950-BSC 2001, Section 8.3.1.3). The evaporation rate at the top of the drip shield would be bounded by the amount of heat available to vaporize water on the upper portion of the drip shield. This heat flow rate into the upper portion of the drip shield was used to determine the maximum volumetric flow rate of incoming seepage water that could be completely vaporized at this location.

I.2.4 WASTE PACKAGE AND DRIP SHIELD DEGRADATION

The radioactive waste placed in the proposed repository would be enclosed in a two-layer waste package. The layers would be of two different materials that would fail at different rates and from different mechanisms as they were exposed to various repository conditions. The outer layer would be a high-nickel alloy metal (Alloy-22) and the inner layer a stainless-steel alloy metal (316NG). To divert dripping water away from the waste package and thereby extend waste package life, a Titanium Grade 7 drip shield would be placed over the waste packages just prior to repository closure. The drip shield would divert water entering the drift from above preventing seep water from contacting the waste package. The *drip shield and waste package degradation models* were used to simulate the degradation of these components (DIRS 153246-CRWMS M&O 2000, pp. 3-79 to 3-91, DIRS 155950-BSC 2001, Section 7, and DIRS 157307-BSC 2001, Enclosure 1). Three main types of degradation were considered in the nominal scenario: humid-air general corrosion, aqueous general corrosion, and stress corrosion cracking. Two additional corrosion processes—microbially induced corrosion and thermal aging/phase instability—were considered to provide enhanced general corrosion on the waste package. General corrosion mechanisms would be conceptually similar for the drip shield and waste package, and were simulated using a common approach. Mechanical failure by rockfall was screened out of the model due to low consequence.

The primary models supplying input to the drip shield and waste package degradation abstractions are the thermal hydrology model and the in-drift geochemical abstraction model. Output from the degradation models is a time-dependent quantitative assessment of the drip shield and waste package degradation and failure. Results include the time to initial breach for the drip shield and the waste package; time to first breach of the waste package by stress corrosion crack failure; and the degree of drip shield and waste package failure as a function of time. The time of the first breach of the waste package would correspond to the start of waste form degradation in the breached package. The output also includes the uncertainty and spatial variation of the degradation information for each waste package and drip shield at different locations (described above as *bins*) within the potential repository. A recent reevaluation of potential early waste package failure mechanisms indicated that improper heat treatment of waste packages could lead to a gross failure of affected waste packages, although the probability of this occurrence is very low. Therefore, improper heat treatment of waste packages is now modeled in the current waste package degradation analysis (DIRS 155950-BSC 2001, Section 7.3.6). An analysis of manufacturing and testing led to a probability distribution for the number of packages that could fail from improper heat treatment of the Alloy-22 closure weld. The resulting distribution is listed in Table I-3. The distribution for waste package failures reflects a very conservative view, because it is assumed that if the outer weld was not properly heat treated the package would automatically fail, even though improper heat treatment would not necessarily result in failure, and the inner weld on the Alloy-22 and the inner stainless steel weld would probably remain intact. This distribution was sampled for each realization of the TSPA model and resulted in early failures of a very small number of waste packages in some of the realizations. This would result in very small releases during the first 10,000 years after closure.

The analysis in this EIS assessed the possible effects of waterborne chemically toxic materials. The analysis did not identify any organic materials as being present in sufficient quantities to be toxic. A screening process eliminated most other materials because they were not of concern for human health effects (see Section I.6.1). Some of the components of the high-nickel alloy (such as chromium, molybdenum, nickel, and vanadium) would be of sufficient quantity and possible toxicity to warrant

Table I-3. Poisson probabilities for improper heat treatment of waste packages.[a]

Number of packages	Proposed Action		Inventory Module 1		Inventory Module 2	
	Probability	Cumulative probability	Probability	Cumulative probability	Probability	Cumulative probability
0	0.76874	0.76874	0.69011	0.69011	0.98669	0.98669
1	0.20218	0.97092	0.25596	0.94608	0.013224	0.999911
2	0.026587	0.99751	0.047468	0.99354	8.8615×10^{-5}	0.9999996
3	2.3308×10^{-3}	0.99984	5.8687×10^{-3}	0.99941	3.9588×10^{-7}	1
4	1.5325×10^{-4}	0.999992	5.4417×10^{-4}	0.999957	1.32464×10^{-9}	1
5	8.0608×10^{-6}	1	4.0367×10^{-5}	0.9999974	3.5555×10^{-12}	1

a. Calculated from the mean Poisson value entered in the performance model.

further analysis. The rate of release of these materials was taken directly from data used for the waste package degradation modeling.

I.2.5 WASTE FORM DEGRADATION

The *waste form degradation model* evaluates the interrelationship among the in-package water chemistry, the degradation of the waste form (including cladding), and the mobilization of radionuclides (DIRS 153246-CRWMS M&O 2000, pp. 3-92 to 3-129 and DIRS 155950-BSC 2001, Sections 9.3.1-9.3.2, 10.3.1, and 10.3.4). The model consists of components that:

- Define the radioisotope inventories for representative commercial spent nuclear fuel and codisposal waste packages (this is the inventory abstraction discussed in more detail in Section I.3.1)

- Evaluate in-package water chemistry—in-package chemistry component abstraction (using chemistry lookup tables developed from detailed process model studies and calculations involving other model parameters)

- Evaluate the matrix degradation rates for commercial spent nuclear fuel, DOE-owned spent nuclear fuel, and high-level radioactive waste forms—waste form matrix degradation component abstractions (a temperature- and pH-dependent rate equation with several parameters, such as rate constants and activation energies, represented by statistical distributions)

- Evaluate the rate of Zircaloy cladding degradation (in the case of commercial spent nuclear fuel)—cladding degradation component abstraction with the following components:

  – Initial failure of Zircaloy cladding represented by a triangular distribution (low, mode, and high fraction of rods failed)

  – Creep failure of Zircaloy cladding represented by a series of triangular distributions, with a low value, mode value and high value, for fraction of rods perforated; each distribution for a specific peak waste package temperature range

  – Localized corrosion of Zircaloy cladding represented as a function of the water flux into the waste package, or a small, constant rate if there is no seepage

  – Assumption of total perforation of all stainless-steel cladding at time zero

  – Seismically induced cladding failure as all cladding would fail when a discrete event frequency of 0.0000011 per year occurred

  - A cumulative distribution of cladding unzipping rate coefficients; the coefficients are multiplied by the fuel matrix dissolution rate to obtain unzipping velocity

  - Effective exposure area of matrix (for radionuclide distribution) as a function of cladding perforation and unzipping

- Evaluate the radionuclide concentrations for aqueous phases—dissolved radionuclide concentration component abstraction (distributions of solubilities as a function of pH and temperature in the waste package; solubilities are also checked for possible limitations due to waste form degradation rate or package inventory)

- Evaluate diffusion of radionuclides in the waste package (DIRS 155950-BSC 2001, Section 10.3.1)

- Evaluate sorption of radionuclides in the waste package (DIRS 155950-BSC 2001, Section 10.3.4)

- Evaluate the waste form colloidal phases—colloidal radionuclide concentration component abstraction (reversible and irreversible colloid models)

I.2.6 ENGINEERED BARRIER TRANSPORT

The waste form would be the source of all radionuclides considered for the engineered barrier system. Radionuclides could be transported downward through the invert and into the unsaturated zone. Transport could occur by diffusion or by advection, depending on the route of the transport. The *engineered barrier system transport abstraction* (DIRS 153246-CRWMS M&O 2000, pp. 3-130 to 3-143) conservatively assumes that diffusion could occur once stress corrosion cracks form, regardless of whether conditions were appropriate for a continuous liquid pathway to exist. Colloid-facilitated transport of radionuclides was included as a transport mechanism. Radionuclides would be transported from the waste package either as dissolved species or bound in, or attached to, colloids.

The abstraction simulates the following transport modes:

- Waste package to invert path
  - Diffusion through stress corrosion cracks
  - Diffusion and advection through patches failed by bulk corrosion

- Invert to unsaturated zone path - Diffusion, sorption and advection through the invert (DIRS 155950-BSC 2001, Section 10.3.3 and 10.3.4)

Diffusion is represented by a diffusion transport equation with an empirical effective diffusivity that is a function of liquid saturation, porosity, and temperature. Sorption on corrosion products is characterized by a linear isotherm (K_D). Advective transport is represented by a liquid transport equation with the velocity determined by the engineered barrier system flow abstraction discussed above.

I.2.7 UNSATURATED ZONE TRANSPORT

Unsaturated zone transport refers to the movement of radionuclides from the engineered barrier system of the proposed repository, through the unsaturated zone, and to the water table. The unsaturated zone would be the first natural barrier to radionuclides that escaped from the potential repository. The unsaturated zone would act as a barrier by delaying radionuclide movement. If the delay was long enough for significant decay of a specific radionuclide, the unsaturated zone could have a significant effect on the ultimate dose from releases of that radionuclide to the environment. The *unsaturated zone transport model* (DIRS 153246-CRWMS M&O 2000, pp. 3-144 to 3-156, and DIRS 155950-BSC 2001, Section 11.3) is used to describe how radionuclides move through the unsaturated zone. The unsaturated zone model considers transport through welded tuff and nonwelded tuff and flow through both the fractures and the rock matrix. In addition, the model accounts for the existence of zeolitic alterations in some regions. These zeolitic tuffs are characterized with low permeability and enhanced radionuclide sorption.

The unsaturated zone water flow would provide the background on which the unsaturated zone transport took place. The model uses the flow fields developed using the unsaturated zone flow model, as described in Section I.2.2. Radionuclides can migrate in groundwater as dissolved molecular species or by being associated with colloids. Five basic processes affect the movement of dissolved or colloidal radionuclides:

- Advection (movement of dissolved and colloidal material with the bulk flow of water) including drift shadow effects on the seepage below the repository (DIRS 155950-BSC 2001, Section 11.3.1)
- Diffusion (movement of dissolved or colloidal material because of random motion at the molecular or colloidal particle scale)
- Sorption (a combination of chemical interactions between solid and liquid phases that reversibly partition radionuclides between the phases)
- Hydrodynamic dispersion (spreading of radionuclides perpendicular to and along the path of flow as they transport caused by localized variations in the flow field and by diffusion)
- Radioactive decay

Sorption is potentially important because it slows, or retards, the transport of radionuclides. Diffusion of radionuclides out of fractures into matrix pores is also a potential retardation mechanism because matrix transport is generally slower than fracture transport. However, sorption and matrix diffusion have less effect on colloids, so radionuclides bound to colloids can be more mobile than radionuclides dissolved in water. Radioactive decay could be important both from quantity reduction of certain radionuclides and the behavior of decay products that can have different transport properties than the decayed radionuclide.

The unsaturated zone transport model was implemented in the TSPA model as an embedded computer code that simulates the three-dimensional transport using a residence-time, transfer-function, particle-tracking technique. The key parameters such as sorption coefficients, diffusion coefficients, dispersivity, fracture spacing, and colloid parameters (partitioning, retardation, colloid size, fraction of colloids exchanging between matrix units) are all input as uncertainty distributions. The results are expressed as breakthrough curves (normalized fraction of total amount of radionuclide arriving at the saturated zone as a function of time) for each radionuclide. These are the inputs for saturated zone transport modeling.

I.2.8 SATURATED ZONE FLOW AND TRANSPORT

The saturated zone at Yucca Mountain is the region beneath the ground surface where rock pores and fractures are fully saturated with groundwater. The upper boundary of the saturated zone is called the water table. The proposed repository would be approximately 300 meters (1,000 feet) above the water table in the unsaturated zone.

As on the surface, underground water flows down the hydraulic gradient. Based on water-level observations in area wells, groundwater near Yucca Mountain flows generally in a north-to-south direction. The major purpose of the *saturated zone flow and transport model* (DIRS 153246-CRWMS M&O 2000, pp. 3-156 to 3-174, and DIRS 155950-BSC 2001, Sections 12.3.1 and 12.3.2) is to evaluate the migration of radionuclides from their introduction at the water table below the potential repository to the point of release to the biosphere (for example, a water supply well). Radionuclides can move through the saturated zone either as a dissolved solute or associated with colloids. The input to the saturated zone is the spatial and temporal distribution of mass flux of radionuclides from the unsaturated zone. The output of the saturated zone flow and transport model is a mass flux of radionuclides in the water used by a hypothetical farming community.

I.2.8.1 Saturated Zone Flow

The *saturated zone flow submodel* (DIRS 153246-CRWMS M&O 2000, pp. 3-157 to 3-164 and DIRS 155950-BSC 2001, Section 12.3.1) takes inputs from the unsaturated zone flow submodel and produces outputs, in the form of flow fields, for the saturated zone transport submodel. The saturated zone flow submodel incorporates a significant amount of geologic and hydrologic data taken from drill holes near Yucca Mountain. The saturated groundwater flow in the vicinity of Yucca Mountain can be estimated by knowing the porosity of the flow media, the hydraulic conductivity, and the recharge of water into the flow media. The primary tool used to describe saturated zone flow is a numerical model formulated in three dimensions. The three-dimensional saturated zone flow model has been developed specifically to determine the groundwater flow field at Yucca Mountain. The model was used to produce a library of flow fields (maps of groundwater fluxes). In addition, a GoldSim-based one-dimensional version of the model was used to provide flow information for a one-dimensional model of transport of radionuclide decay products.

I.2.8.2 Saturated Zone Transport

The *saturated zone transport submodel* (DIRS 153246-CRWMS M&O 2000, pp. 3-157 to 3-164, and DIRS 155950-BSC 2001, Section 12.3.2) takes inputs in the form of radionuclide mass fluxes from the unsaturated zone transport submodel and produces outputs in the form of radionuclide mass fluxes to the biosphere model. The saturated zone transport model incorporates a substantial amount of laboratory and field data taken from a variety of sources.

Radionuclides released from a repository at Yucca Mountain to the groundwater would enter the saturated zone beneath the repository and would be transported first southeast, then south, toward the Amargosa Desert. The radionuclides could be transported by the groundwater in two forms: as dissolved species or associated with colloids. Dissolved species typically consist of radionuclide ions complexed with various groundwater species, but still at molecular size. Colloids are particles of solids, typically clays, silica fragments, or organics, such as humic acids or bacteria, that are larger than molecular size, but small enough to remain suspended in groundwater for indefinite periods. Colloids are usually considered to have a size range of between a nanometer and a micrometer. A radionuclide associated with a colloid can transport either attached to the surface or bound within the structure of the colloid.

Transport through the saturated zone was primarily modeled using a three-dimensional particle-tracking method (DIRS 153246-CRWMS M&O 2000, pp. 3-168 to 3-169). The three-dimensional transport model was not used directly by the TSPA model. It was used to generate a library of breakthrough curves—distributions of transport times that are used, along with a time-varying source term from the unsaturated zone, to calculate the releases at the geosphere/biosphere boundary. The model accounts for the flow of groundwater and its interaction with varying media along the flow path. In the volcanic rocks that comprise the saturated media in the immediate vicinity of Yucca Mountain, groundwater flows primarily through fractures, while a large volume of water is held relatively immobile in the surrounding rock matrix. Radionuclides would travel with the moving fracture water but, if dissolved, could diffuse between the matrix water and fracture water. This transfer between fracture and matrix water is characteristic of a dual-porosity system. The saturated zone transport model is a dual-porosity model.

The media at greater distances from Yucca Mountain are alluvial gravels, sands and silts. The model simulates these areas as a more uniform porous material. While there is a possibility for channelized flow in the alluvium, current data indicate little evidence of dual-porosity behavior that would indicate this (DIRS 155950-BSC 2001, p. 12-23).

A one-dimensional saturated zone transport model was used to account for decay and ingrowth during transport. This model was incorporated directly in the GoldSim model as a series of pipes. The advantage of using the one-dimensional model is that the radionuclide masses can be accounted for directly. The disadvantage is that the flow and transport geometry is necessarily simplified.

I.2.9 BIOSPHERE

If the radionuclides were removed from the saturated zone in water pumped from wells, the radioactive material could result in dose to humans in several ways. For example, the well water could be used to irrigate crops that would be consumed by humans or livestock, to water stock animals that would be consumed by humans as dairy or meat products, or to provide drinking water for humans. In addition, if the water pumped from irrigation wells evaporated on the ground surface, the radionuclides could be left as fine particulate matter that could be picked up by the wind and inhaled by humans. The *biosphere pathway model* (DIRS 153246-CRWMS M&O 2000, pp. 3-175 to 3-187) was used to predict radiation exposure to a person living in the general vicinity of the repository if there was a release of radioactive material to the biosphere after closure of the proposed repository. The model uses a biosphere dose conversion factor that converts saturated zone radionuclide concentrations to annual individual radiation dose. The biosphere dose conversion factor was developed by analyzing the multiple pathways through the biosphere by which radionuclides can affect a person. The biosphere scenario assumed a *reference person* living in the Amargosa Valley region at various distances from the repository. People living in the Town of Amargosa Valley would be the group most likely to be affected by radioactive releases. An adult who lives year-round at this location, uses a well as the primary water source, and otherwise has habits (such as the consumption of local foods) similar to those of the inhabitants of the region. Because changes in human activities over millennia are unpredictable, the analysis assumed that the present-day reference person described future inhabitants. Strict definitions for the reference person (the Reasonably Maximally Exposed Individual, or RMEI) have been prescribed in 40 CFR Part 197. The chemically toxic materials were not evaluated in the biosphere model because there are no usable comparison values for radiologic and nonradiologic dose. Rather, a separate analysis of concentrations of these materials was made. The concentrations were then compared to available regulatory standards, such as the Maximum Contaminant Level Goal if available, or to the appropriate Oral Reference Dose.

The biosphere is the last component in the chain of TSPA model subsystem components. There are two connections between the biosphere submodel and other TSPA model submodels. One is for the groundwater irrigation scenario (nominal scenario), where the biosphere is coupled to the saturated zone flow and transport model; and the other is for the disruptive scenario, where the biosphere is coupled to the volcanic dispersal model. For the human intrusion scenario, the biosphere model is coupled with the saturated zone flow and transport model, and the event is treated as a perturbation to the nominal scenario. The groundwater path doses are based on specific paths of groundwater flow derived from regional data.

The primary result of the biosphere modeling is the construction of biosphere dose conversion factor distributions for the groundwater-release scenarios and the volcanic-ash-release scenario (DIRS 157307-BSC 2001, all). For the nominal scenario, well withdrawal of groundwater is the source of water for drinking, irrigation, and other uses. A farming community at the point of withdrawal would use the water at a rate based on surveys of current usage. The hypothetical farming community consists of between 15 and 25 farms supporting about 100 people. All radionuclides reaching this community in groundwater were assumed to be mixed in the volume of water that the community would use (this is the concept of full "capture" of the total plume of contamination). The water usage was input as a distribution of values based on current water usage data. The exposure pathways routes taken by radionuclides through the biosphere from the source to an individual are typical for a farming community in this environment. Farming activities usually involve more exposure pathways than other human activities in the Yucca Mountain region, including ingestion of contaminated water and locally produced food as well as inhalation and direct exposure from soil contamination intensified by the significant outdoor activity inherent in a farming lifestyle.

During periods of very wet climate, the Amargosa Desert is actually a lake and the irrigated farm scenario on which the biosphere model is based is not applicable. This is consistent with regulatory guidance that indicates no attempt should be made to project future human behavior and lifestyles (even if driven by climate change). The approach used is conservative because the use of groundwater for irrigation and domestic purposes has the effect of bringing up relatively concentrated solutions of contaminants. In a scenario where the Amargosa Desert is a lake (as it was 20,000 years ago), this large quantity of water would dilute the radionuclides to very low concentrations. Furthermore, the use of water would follow a greatly altered pattern. Consideration of all this leads to the conclusion that peak doses would be much lower than those projected in the current analysis.

I.2.10 VOLCANISM

Igneous activity (flow of volcanic material as in a volcanic eruption) has been identified as a disruptive event that has a potential to affect repository long-term performance. Yucca Mountain is in a region that has had repeated volcanic activity in the geologic past. Although the probability of recurrence at Yucca Mountain during the next 10,000 years is small, it is greater than 1 chance in 10,000 and is, therefore, retained as a scenario.

If igneous activity occurred at Yucca Mountain, possible effects on the repository could be grouped into three areas:

- Igneous activity that would not directly intersect the repository (can be shown to have no effect on dose from the repository)

- Volcanic eruptions in the repository that would result in waste material being entrained in the volcanic magma or pyroclastic material, bringing waste to the surface (resulting in atmospheric transport of volcanic ash contaminated with radionuclides and subsequent human exposure downwind)

- An igneous intrusion intersecting the repository (no eruption but damage to waste packages from exposure to the igneous material that would enhance release to the groundwater and, thus, enhance transport to the biosphere)

Based on studies of past activity in the region, probabilities for different types of igneous activity were estimated. Each type of event was described in detail based on observation of effects of past activities. These descriptions include geometry of intrusions, geometry of eruptions, physical and chemical properties of volcanic materials, eruption properties (velocity, power, duration, volume, and particle characteristics). Most of the parameters describing the igneous activity were entered in the modeling as probability distributions.

A collection of different modeling approaches was used to develop responses to the different types of activity described above (DIRS 153246-CRWMS M&O 2000, pp. 3-187 to 3-216 and DIRS 157307-BSC 2001, Enclosure 1).

I.2.11 HUMAN INTRUSION

Human intrusion was modeled based on a stylized scenario that is a conceptualization of the assumptions outlined in the Environmental Protection Agency standard (DIRS 157307-BSC 2001, Enclosure 1). The assumptions are based on recommendations of the National Research Council of the National Academy of Sciences. The Council observed that it is not possible to predict human behavior over the extremely long periods of concern and prescribed the scenario as a reasonable representation of typical inadvertent intrusion.

The models used were the same as those for the nominal scenario, except a source term was introduced for the time of the intrusion. This source term is characteristic of direct penetration of a waste package with a drill bit (DIRS 157307-BSC 2001, Enclosure 1).

I.2.12 NUCLEAR CRITICALITY

A nuclear criticality occurs when sufficient quantities of fissionable materials come together in a precise manner and the required conditions exist to start and sustain a nuclear chain reaction. One of the required conditions is the presence of a moderator, such as water, in the waste package. The waste packages would be designed to make the probability of a criticality occurring inside the waste package extremely small. In addition, based on an analysis of anticipated repository conditions, it is very unlikely that a sufficient quantity of fissionable materials could accumulate outside the waste packages in the precise configuration and with the required conditions to create a criticality. If, somehow, an external criticality was to occur, analyses indicate that it would have only minor effects on repository performance. In the unlikely event that a criticality occurred, there would be a short-duration localized rise in temperature and pressure, as well as an insignificant increase in the repository radionuclide inventory. No measurable effect on repository performance would result from this event (DIRS 153849-DOE 2001, p. 4-416).

I.2.13 ATMOSPHERIC RADIOLOGICAL CONSEQUENCES

In addition to the groundwater pathway, the analysis of long-term performance evaluated potential consequences of the release of radioactive gases into the environment. An analysis separate from the groundwater modeling described in the previous sections was used to forecast such consequences. The model used results from the waste package degradation models to evaluate when waste packages and fuel cladding would fail and, therefore, release contained radioactive gases. This model provided input to release and transport estimates for the atmospheric pathway. Section I.7 contains details of this analysis.

I.3 Inventory

This section discusses the inventories of waterborne radioactive materials used to model radiological impacts and of some nonradioactive, chemically toxic waterborne materials used in the repository environment that could present health hazards. This section also discusses the inventory of atmospheric radioactive materials.

I.3.1 INVENTORY FOR WATERBORNE RADIOACTIVE MATERIALS

There would be more than 200 radionuclides in the materials placed in the repository (see Appendix A of this EIS). In the Proposed Action, these radionuclides would be present in five basic waste forms: commercial spent nuclear fuel, mixed-oxide fuel and plutonium ceramic (called here *plutonium disposition waste*), borosilicate glass formed from liquid wastes on various DOE sites known as high-level radioactive waste, DOE-owned spent nuclear fuel, and naval spent nuclear fuel (DIRS 153246-CRWMS M&O 2000, Figure 3.5-4). In the repository, these wastes would be placed in several